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Cryogenic Evaluation of an Advanced DC/DC Converter Module for Deep Space Applications

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***Abstract-* DC/DC converters are widely used in power management, conditioning, and control of space power systems. Deep space applications require electronics that withstand cryogenic temperature and meet a stringent radiation tolerance. In this work, the performance of an advanced, radiation-hardened (rad-hard) commercial DC/DC converter module was investigated at cryogenic temperatures. The converter was investigated in terms of its steady state and dynamic operations. The output voltage regulation, efficiency, terminal current ripple characteristics, and output voltage response to load changes were determined in the temperature range of 20 to –140 °C. These parameters were obtained at various load levels and at different input voltages. The experimental procedures along with the results obtained on the investigated converter are presented and discussed.**

I. INTRODUCTION

In many future space missions, such as outer planetary exploration and deep space probes, electrical and electronic power components and systems must operate reliably and efficiently in very low temperature environments. For example, an inter-planetary probe launched to explore the rings of Saturn would experience an average temperature of about –183 °C. Presently, spacecraft operating in the cold environment of deep space carry on-board a large number of radioisotope heating units to maintain an operating temperature for the electronics of approximately 20 °C. This is not an ideal solution because the radioisotope units are always producing heat, even when the spacecraft is already too hot, thus requiring an active thermal control system for the spacecraft. Electronics capable of operation at cryogenic temperatures will not only tolerate the hostile environment of deep space but also reduce system size and weight by eliminating the heating radioisotope units and associated structures thereby; reducing system development and launch costs, improving reliability and lifetime, and increasing energy densities.

The Low Temperature Electronics Program at the NASA Glenn Research Center (GRC) focuses on research and development of electrical components and systems suitable for applications in deep space missions. Research is being conducted on components and systems for use down to cryogenic temperature (–196 °C). These include commercially available semiconductor switching devices, resistors, magnetic components, capacitors, integrated circuits and DC/DC converter modules. Also, a number of DC/DC converters have been built and characterized in-house at low temperatures. The converters were designed or modified to operate from room temperature to –196 °C using commercially available components. These systems had output power range from 5 W to 1 kW with switching frequencies of 50 to 200 kHz. [1–14].

In this work, an advanced commercial-off-the-shelf modular DC/DC converter has been investigated for low temperature operation. The converter has a high power density (30 W/in^3) and has been space-qualified in terms of radiation tolerance. It is a single-ended forward converter with a constant switching frequency of 550 kHz. It has a wide input voltage range of 16 to 40 V, an output voltage of 3.3 V and a power rating of 10 W. Its operating temperature range is specified between –55 °C to 125 °C. The module was investigated in terms of its steady state output voltage regulation, efficiency, terminal current ripple characteristics, and dynamic response of the output voltage to a step change in load. These properties, which were determined in the temperature range of 20 to –140 °C, were obtained at various load levels and at different input voltages. The experimental procedures along with the experimental data obtained on the investigated converter are presented and discussed.

II. Experimental Setup and Procedures

The tests on the converter were performed using an environmental chamber utilizing liquid nitrogen as the coolant. A temperature rate of change of 10 °C/min was used throughout this work. The module was investigated in the temperature range of 20 to –140 °C at a decrement of 20 °C. At a given temperature, these properties were obtained at various input voltages and at different load levels from no-load to full-load conditions. At every test temperature, the test article was allowed to soak at that temperature for a period of 30 minutes before any measurements were made. After the last measurement was taken at the lowest temperature, the converter was allowed to stabilize to room temperature, and then the measurements were repeated at room temperature to determine the effect of thermal cycling on the converter's performance.

III. Results and Discussions

The converter was evaluated under steady state and dynamic conditions. In the steady state, the converter output voltage regulation, efficiency, and input and output current distortions were investigated. At a given temperature, these properties were obtained at various input voltages and at different load levels, from no-load to full-load conditions.

The dynamic characteristics of the converter were obtained by monitoring the transient response of the output voltage due to a step change in the load. Two responses were recorded, one from no load to full load and the other from full load to no load.

A. *Steady State Performance*

The output voltage and efficiency of the converter at various input voltage and load levels as a function of temperature are shown in Figures 1 through 4. These parameters are obtained utilizing input voltages of 16, 24, 32, and 42 V for loads of 0.5, 1.0, 1.5, 2.0, and 2.5 A. The converter exhibited good voltage regulation with temperature down to –100 °C. This trend is maintained regardless of the load level to which the converter is subjected. Below –100 °C, however, the converter started to display inconsistent behavior in its voltage regulation, particularly with an applied input voltage of 16 V. At this voltage level, the efficiency of the converter tends to slightly decrease with a decrease in test temperature down to –100 °C, as shown in Figure 1. This decrease becomes more significant at temperatures below –100 °C. At any given test temperature, the efficiency increased as the load was increased. At temperatures below –100 °C, the efficiency is at minimum as the converter exhibits some loss in output regulation.

At input voltage higher than 16 V, the converter displayed better stability in its voltage regulation throughout the entire test temperature range from 20 to –140 °C, as shown in Figures 2 to 4. Such is the case at any load level investigated between 0.5 and 2.5 A. The efficiency of the converter, displayed similar behavior to that observed under 16 V input between 20 and –100 °C. Once again, the efficiency, at a given test temperature, has the highest value when the maximum loading level was applied to the converter.

Waveforms of the converter output voltage ripple, the output current ripple, and the input current ripple at room temperature (25 °C) and at a low temperature (–100 °C) are shown in Figures 5 and 6 for light load and heavy load, respectively. Theses waveforms were obtained using an input voltage of 16 V. No effect of temperature can be observed as no significant variations occur in these waveforms.

Figures 7 and 8 show the same waveforms both at room temperature (25 °C) and at the low temperature (–100 °C) for high input voltage of 40 V. Once again, these properties do not undergo much change in their waveforms due to the temperature variation from 20 to –100 °C, regardless of the applied load. The level of the applied input, however, seems to influence these properties as evident from the increase in the frequency as well as the amplitude of the ripples as higher voltages are applied.

B. *Dynamic Performance*

The dynamic response for the converter, represented by output voltage response to a step change in the load current, is shown in Figures 9 and 10. The step change from full load to no load exhibited different dynamic response compared to that of a step change from no load to full load. The different responses are a clear indication of the nonlinear behavior of the module and may also reflect the effect of low temperature on the components and devices in the converter.

IV. Conclusions

An advanced radiation-hardened DC/DC converter was characterized in terms of its performance as a function of temperature in the range of 20 to –140 °C. The converter was evaluated with respect to its steady state output voltage regulation, efficiency, output voltage ripple; input current ripple and output current ripple at various input voltage levels and loads. In general, this converter displayed good performance in regulation, efficiency and dynamic characteristics with temperature down to –100 °C. Some instability is observed as the temperature is decreased further. More testing under long-term thermal exposure is needed to fully characterize this converter for potential application in low temperature environments.

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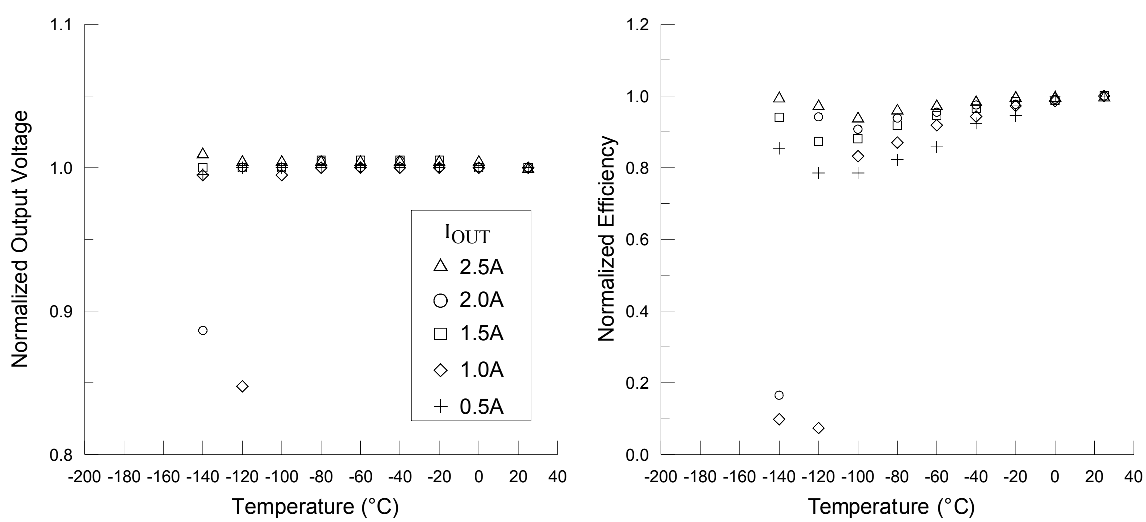

Figure 1. Output voltage and efficiency versus temperature at various loads and input voltage of 16 V.

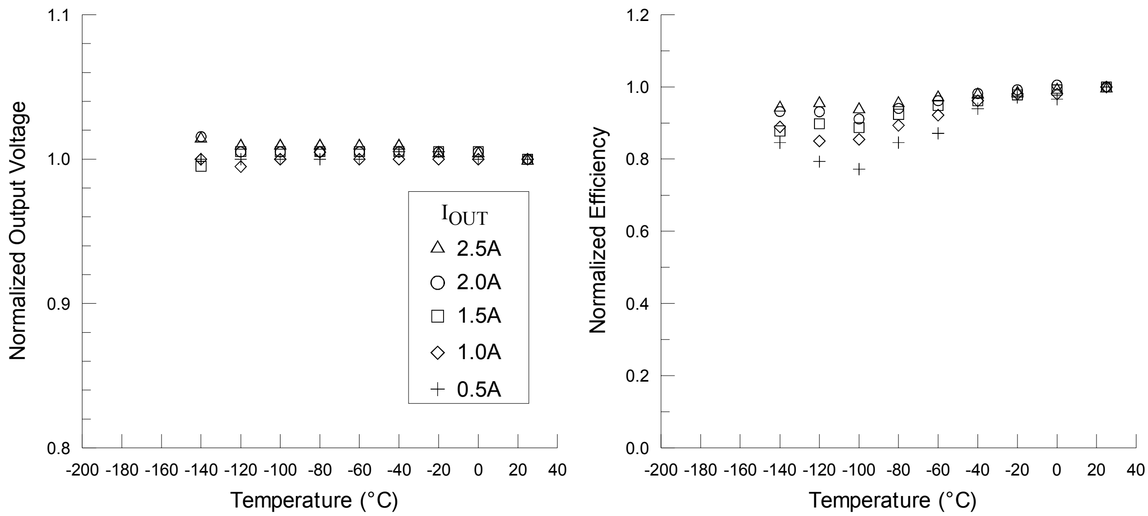

Figure 2. Output voltage and efficiency versus temperature at various loads and input voltage of 24 V.

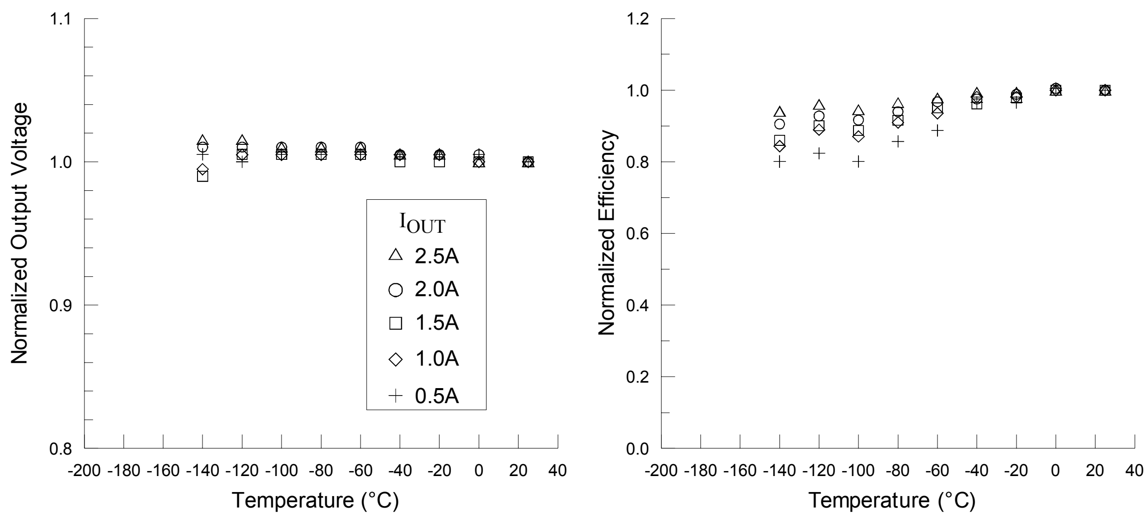

Figure 3. Output voltage and efficiency versus temperature at various loads and input voltage of 32 V.

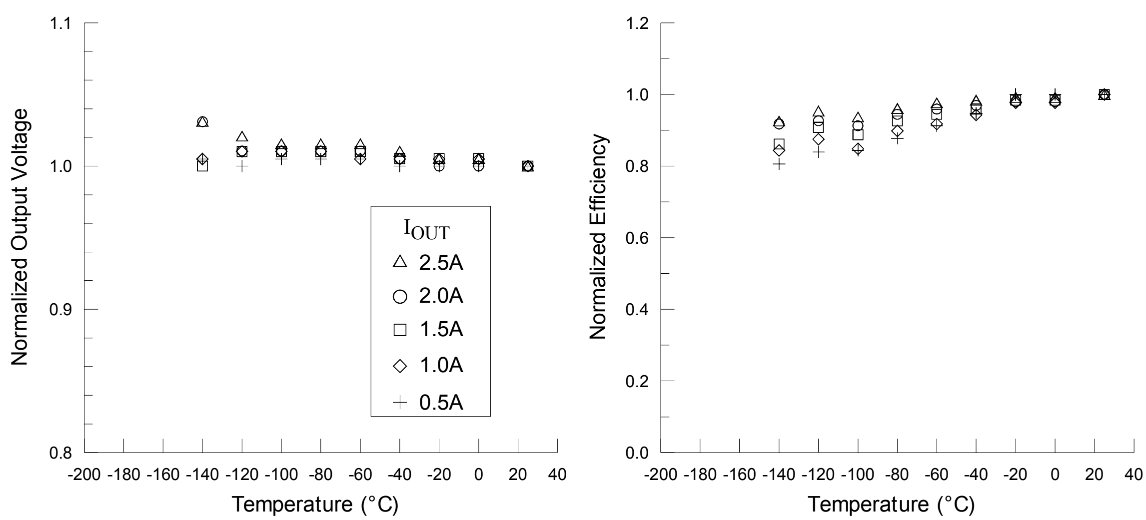

Figure 4. Output voltage and efficiency versus temperature at various loads and input voltage of 40 V.

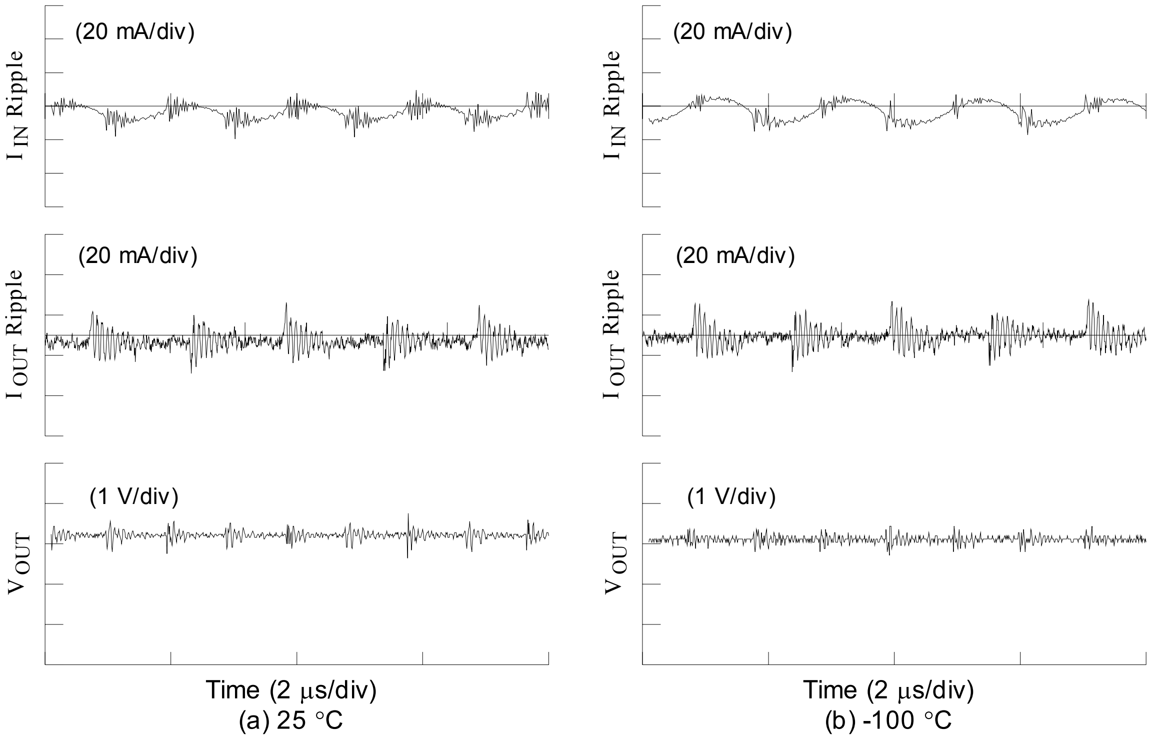

Figure 5. The converter ripple characteristics at low input voltage (16 V) and under light load (1.0 A).

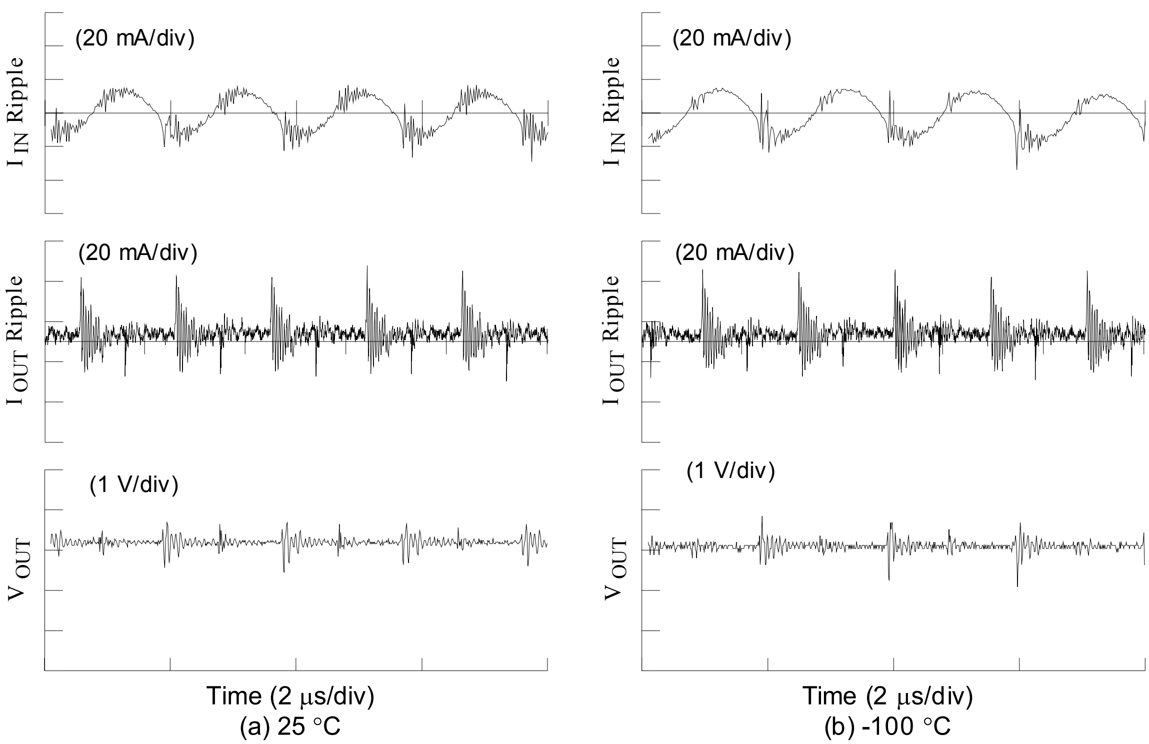

Figure 6. The converter ripple characteristics at low input voltage (16 V) and under heavy load (2.5 A).

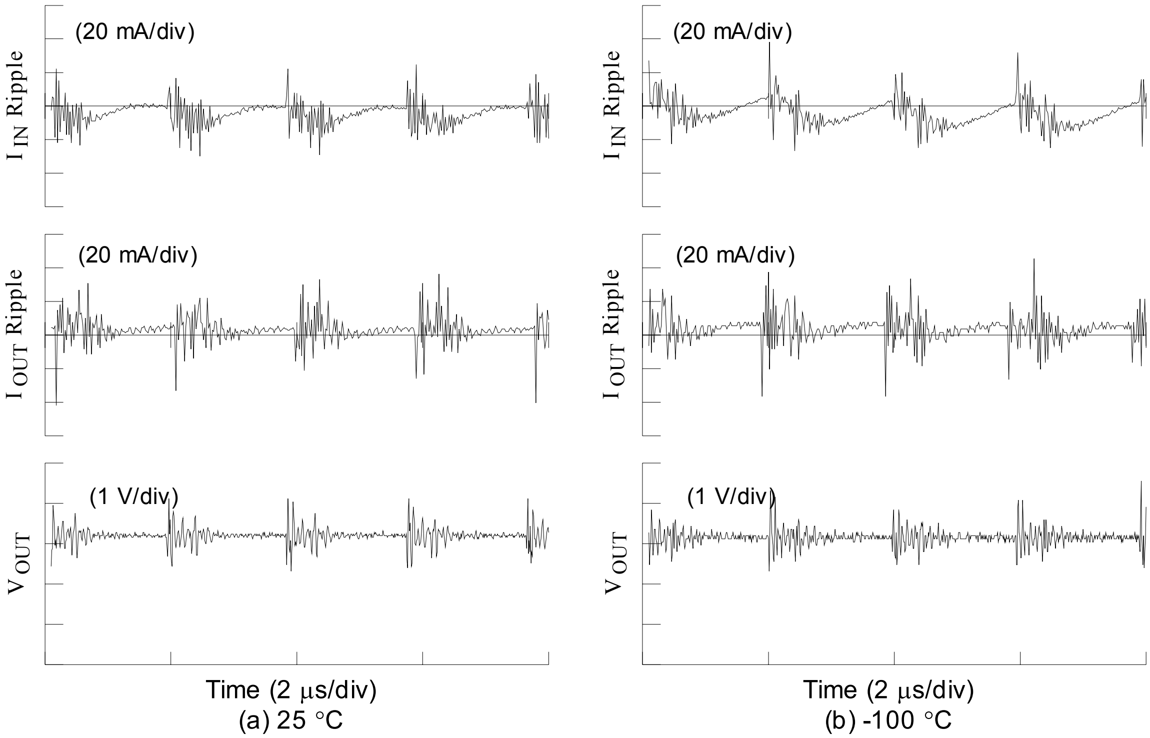

Figure 7. The converter ripple characteristics at high input voltage (40 V) and under light load (1.0 A).

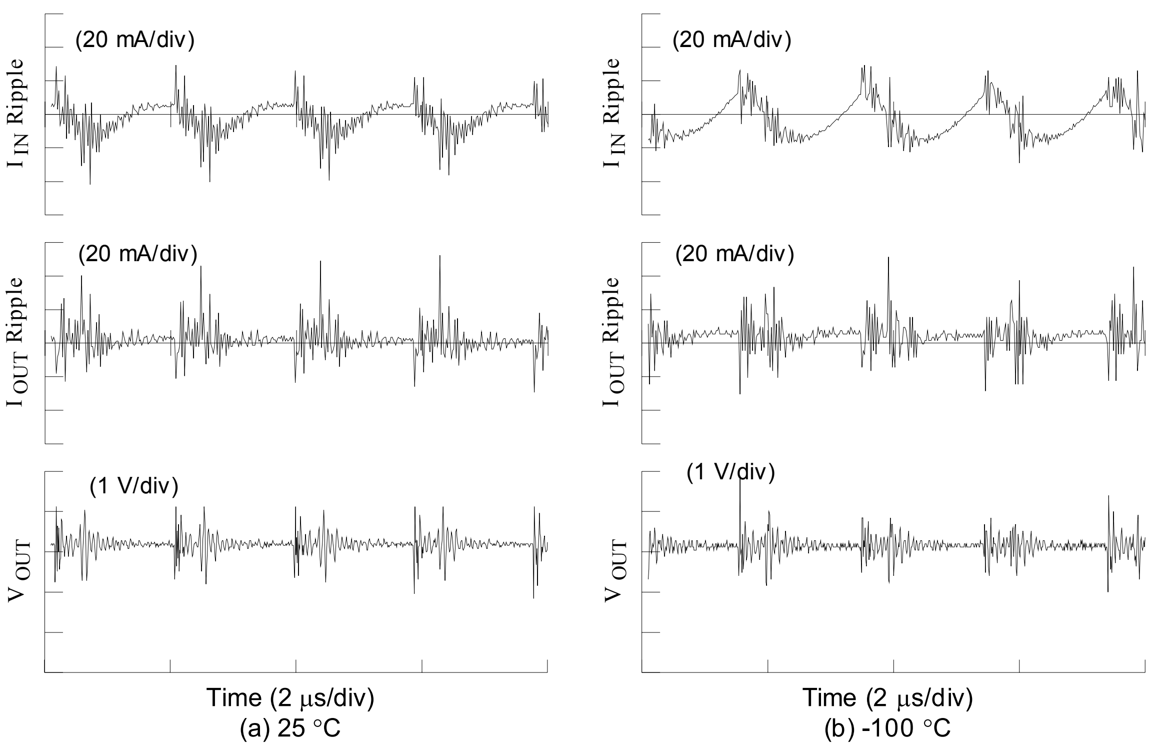

Figure 8. The converter ripple characteristics at high input voltage (40 V) and under heavy load (2.5 A).

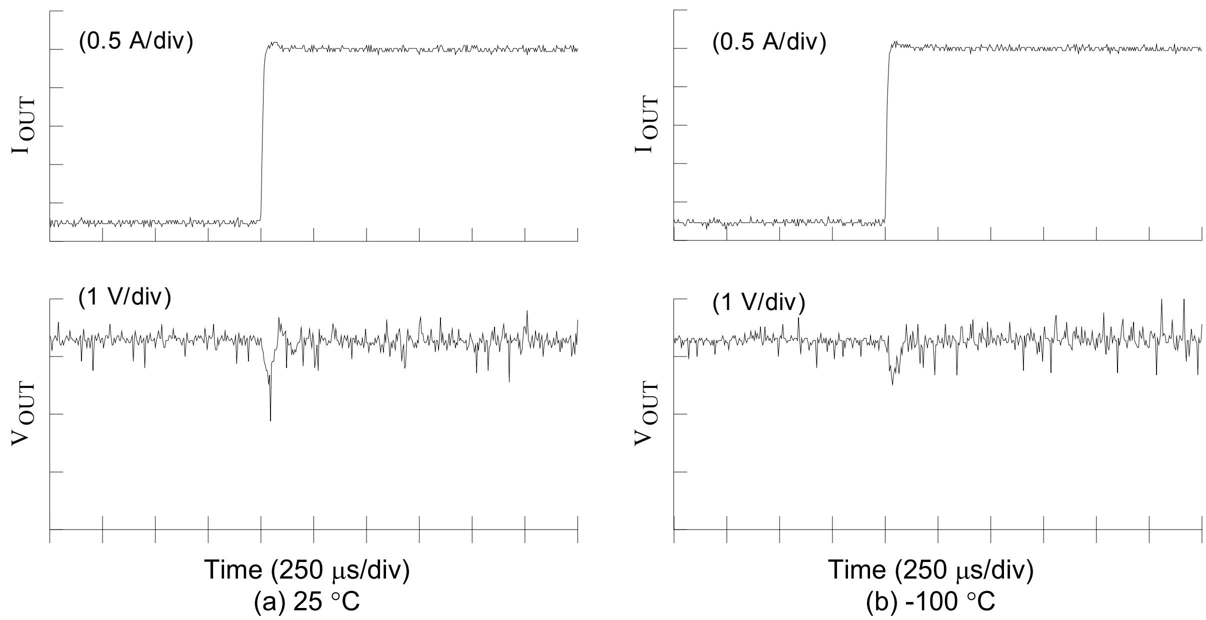

Figure 9. The converter dynamic response to a step change from no-load to full-load at an input voltage of 16 V.

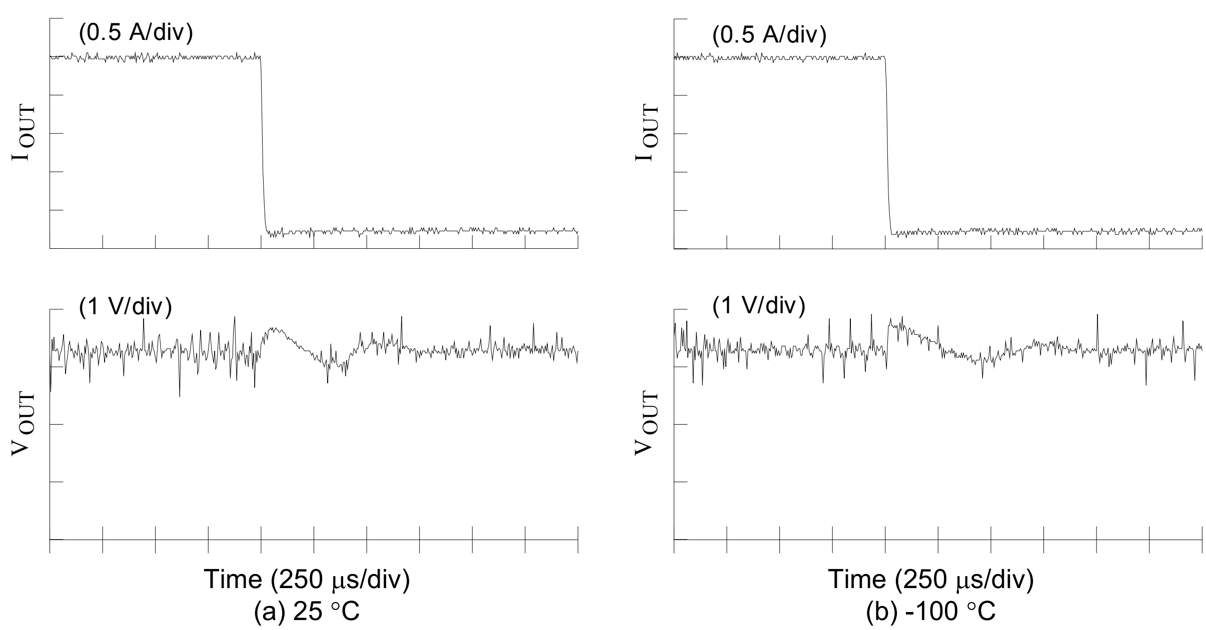

Figure 10. The converter dynamic response to a step change from full-load to no-load at an input voltage of 16 V.

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13. ABSTRACT ***(Maximum 200 words)***

DC/DC converters are widely used in power management, conditioning, and control of space power systems. Deep space applications require electronics that withstand cryogenic temperature and meet a stringent radiation tolerance. In this work, the performance of an advanced, radiation-hardened (rad-hard) commercial DC/DC converter module was investigated at cryogenic temperatures. The converter was investigated in terms of its steady state and dynamic operations. The output voltage regulation, efficiency, terminal current ripple characteristics, and output voltage response to load changes were determined in the temperature range of 20 to –140 °C. These parameters were obtained at various load levels and at different input voltages. The experimental procedures along with the results obtained on the investigated converter are presented and discussed.

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